Collaborative Communications in Wireless Networks Without Perfect Synchronization

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1. Introduction

- Collaborative communications
  - multiple nodes perform transmission or reception cooperatively in dense wireless networks
  - emulate antenna arrays by group of single antennas
  - use low-cost single devices for high performance, capacity, reliability

1. Introduction

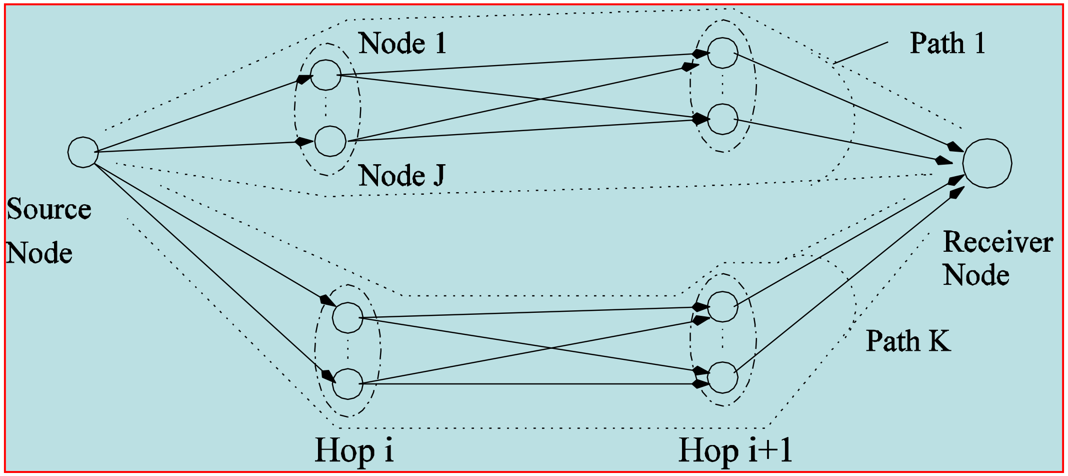
- Typical application scenarios
  - Military: collaboration among group of highly mobile devices carried by soldiers or vehicles
  - Sensor network: collaboration among densely deployed sensors to compensate for the limited capability/reliability of each single sensor
  - Commercial: collaboration among mobiles in cellular systems, WLAN, where mobiles become cheaper and dense

2. Benefits: Implementation Aspect

- Resolve the problem that mobile nodes have no antenna arrays
- Low cost compared with physical arrays
- Easy system development and realization
- Convenience of upgrading existing systems
  - e.g., what can we do with extra WLAN base stations?

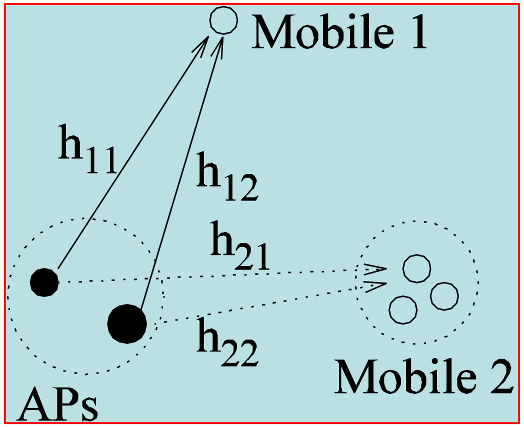
2. Benefits: Performance Aspect

- Enhance transmission power efficiency through cooperative diversity
  - Both macro-diversity and micro-diversity
- Enhance bandwidth efficiency through cooperative MIMO transmissions



2. Benefits: Performance Aspect

- Physical-layer guaranteed security for wireless networks with cooperative beamforming
  - Wireless boundary control, beam-steering/nulling, location/visualization
- Network reliability and fault tolerance
- Assist blind equalization



3. Challenges

- Collaboration protocol and overhead
- Synchronization among distributed nodes
  - Mismatch: carrier frequency, carrier phase, timing, timing phase
  - Due to: noise, parameter drifting, PLL tracking error, devices designed by different companies (inter-operability)
- Information exchange among transmitters or receivers
  - Possible way: use WPAN, UWB, HF to implement high-rate short-range link
- Upgrade existing system with minimum changes
  - e.g., use collaborative communications in WLAN for higher rate, longer range, or security

3. Challenges

- Synchronization problem makes distributed cooperative transmissions a completely new area
  - Carrier mismatch: time-varying channel
  - Timing mismatch: unequal symbol rate
  - Timing phase mismatch: dispersive channel
- Mixture signal structure may be destroyed
  - Traditional array processing such as STBC may not be directly applicable
- Different from existing TDMA,FDMA,CDMA, or array transmissions

4. Cooperative Transmission in Sensor Networks

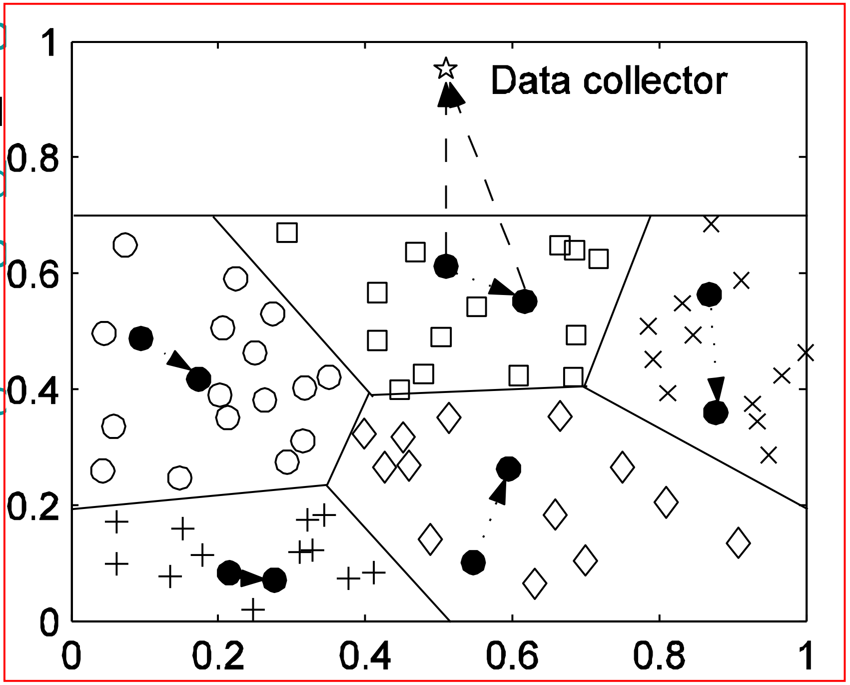
- Sensor network is a potential area for cooperative transmissions
  - enhance transmission energy efficiency
- Existing works:
  - STBC-encoded transmission protocols, diversity benefits, energy efficiency analysis
- Problems:
  - collaboration overhead, synchronization, applicability of flat-fading channel model
  - Is cooperative transmission advantageous?

4. Cooperative Transmission in Sensor Networks

- Apply STBC-encoded cooperative transmission in LEACH (a typical networking/communication protocol)
  - Protocol modification and overhead analysis
  - Synchronization analysis and channel model
  - Overall energy efficiency analysis
  - Simulations & conclusions

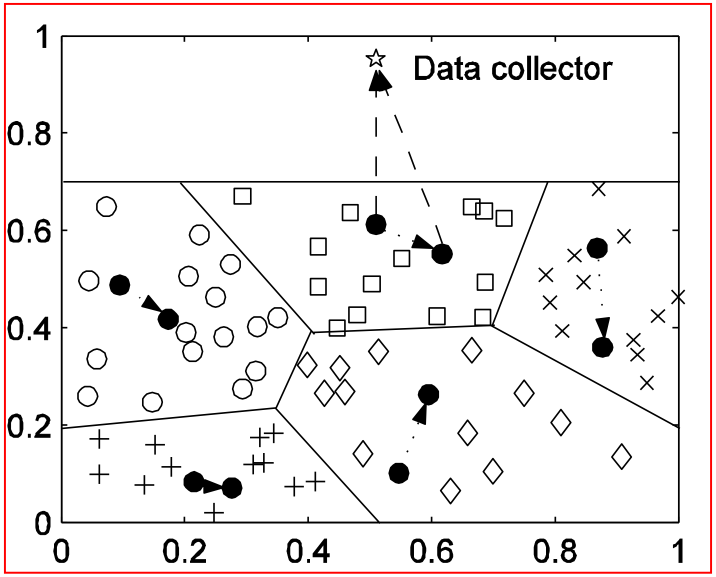
4. Cooperative Transmission in Sensor Networks

- Protocol modification & overhead analysis
  - Advertisement to determine cluster head
  - Cluster setup
    - one-byte more transmissio
  - TDMA transmission schedu
    - determine secondary head
    - one-byte more transmissio
  - Data transmission
    - Primary → secondary head
    - Cooperative transmission
      from heads to collector
- Overhead is small



4. Cooperative Transmission in Sensor Networks

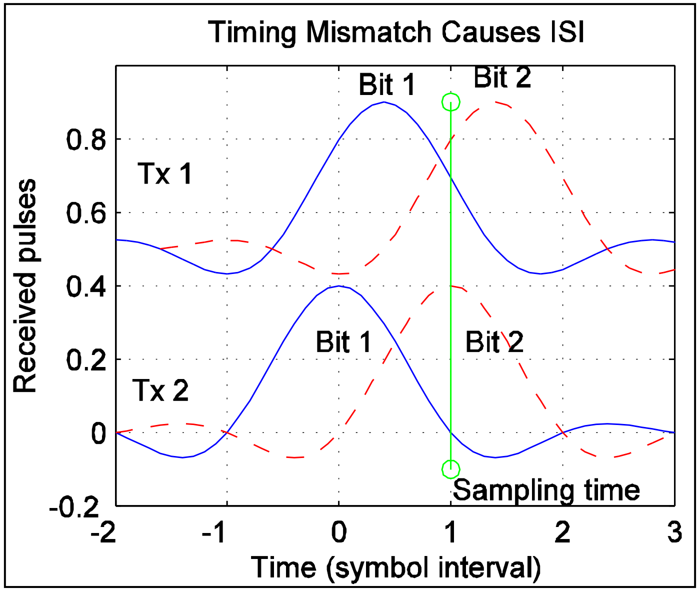
- Synchronization analysis & channel model
  - Secondary heads synchronize frequency/timing to primary heads
  - Carrier phase & timing phase asynchronism contributes to channels → ISI
- Received signal model

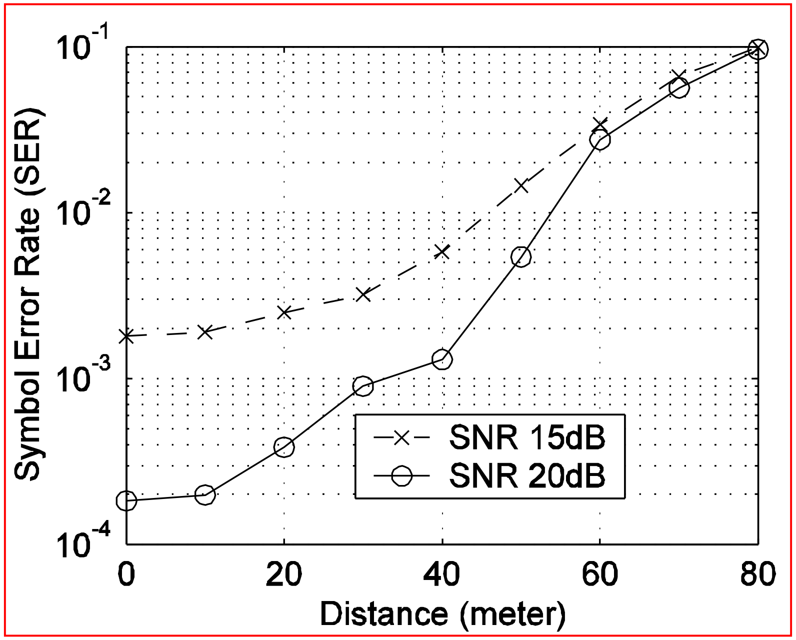


$$r(t) = \mathrm{Re}[\sum_{i=1}^{J} \sum_{k=-\infty}^{\infty} a_i b_i(k) p(t - kT - \tau_i) e^{j(2\pi f_c t - \theta_i)} + w(t)]$$

$$x(n) = \sum_{i=1}^{J} a_i e^{-j\theta_i} [p(\tau - \tau_i) b_i(n) + \sum_{l \neq n} p(lT + \tau - \tau_i) b_i(n - l)] + v(n)$$

- Synchronization analysis & channel model
  - Need to limit the distance among cooperative sensors for omissible ISI → flat fading channel model





4. Cooperative Transmission in Sensor Networks

- Overall energy efficiency analysis
  - Cooperative transmission energy efficiency >> single transmission energy efficiency
  - Consider collaboration overhead, circuit energy, then

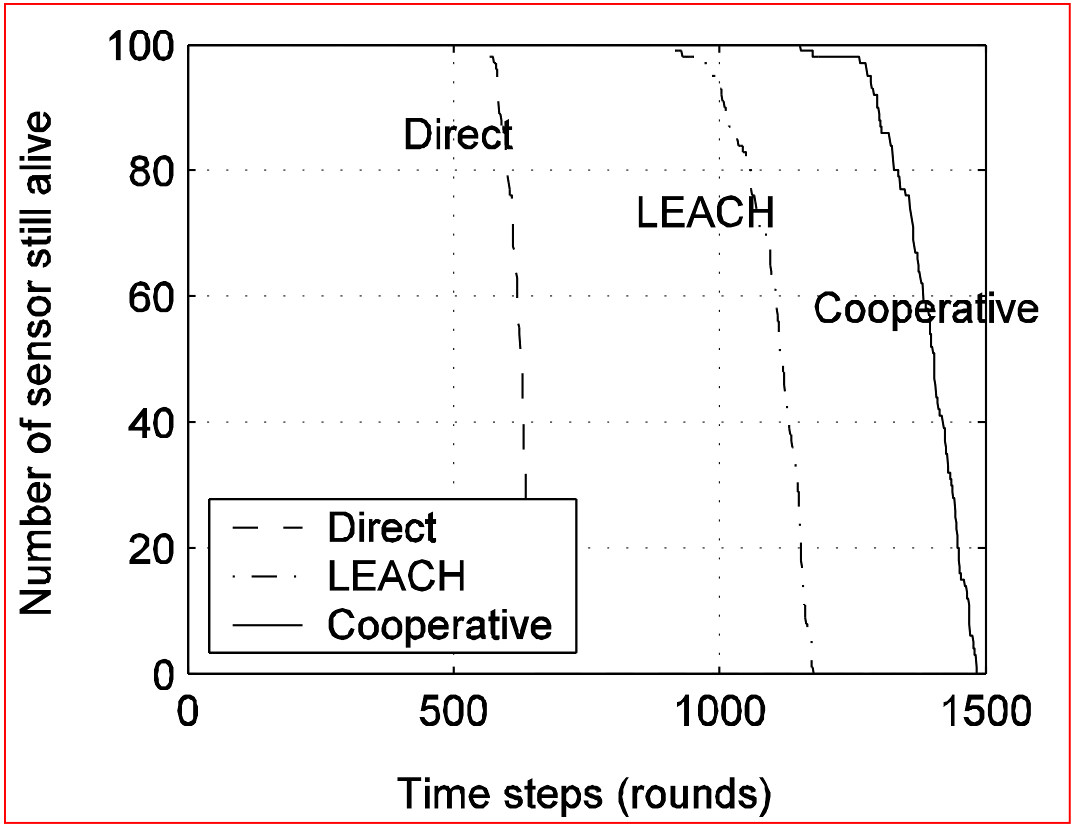
    If cooperative transmission distance is greater than

$$d = \sqrt{[(J+1)\frac{k_J}{k} + J - 2]\frac{E_c}{E_{RF}}}$$

Cooperative transmission is still advantageous.

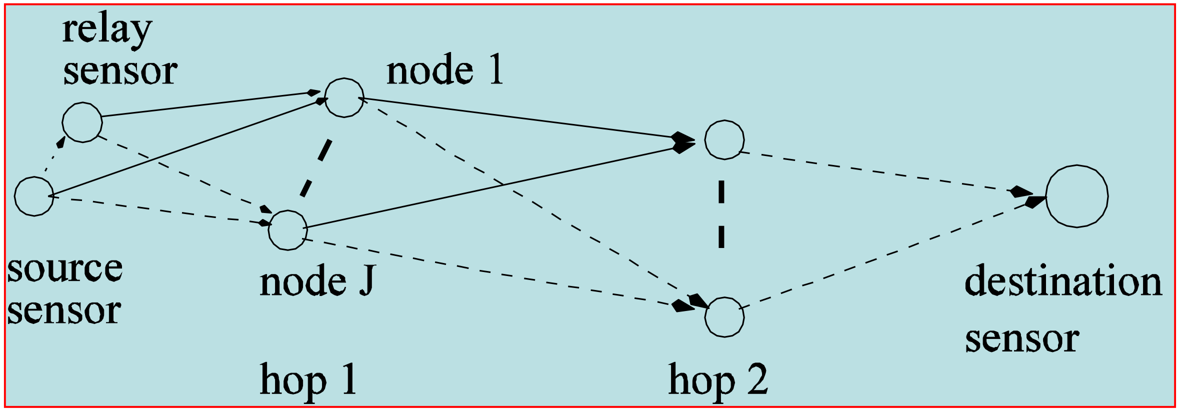
4. Cooperative Transmission in Sensor Networks

- Simulations
- For J=2,3,4, 5, we find d=39,57,69,87 meters
- Cooperative transmission is useful in sensor networks



5. Cooperative STBC for Distributed Transmissions

- Existing work on cooperative STBC: idealized synchronization
- What if synchronization is imperfect?
  - e.g., d is very large for better macro-diversity
- Timing synchronization may be impossible in multi-hop cooperative transmission networks



5. Cooperative STBC for Distributed Transmissions

- Effect of imperfect synchronization
  - Carrier frequency
    - time-varying channels: constraint on block length
  - Symbol timing
    - Unequal symbol rate: constraint on block length
    - Unequal delay: structure of STBC signal destroyed
  - Timing phase
    - Dispersive channels: equalization required

5. Cooperative STBC for Distributed Transmissions

	Slot 1	Slot 2
Node 1	$s_1(0)$ ······· $s_1(N\text{-}1)$	$-s_2^*(N\text{-}1)$ ········ $-s_2^*(0)$
Node 2	$s_2(0)$ ······· $s_2(N\text{-}1)$	$s_1^*(N\text{-}1)$ ········ $s_1^*(0)$

Special: J=2 nodes per cluster

General: J nodes per cluster

node j: $s_j(n)$ for all j	node1: $-s_2^*(N\text{-}n)$ node2: $s_1^*(N\text{-}n)$	……	node i: $-s_j^*(N\text{-}n)$ node j: $s_i^*(N\text{-}n)$	……	node J-1: $-s_J^*(N\text{-}n)$ node J: $s_{J-1}^*(N\text{-}n)$
Frame 0	Frame 1	……	Frame $p_{i,j}$	……	Frame P

- Proposed cooperative STBC transmission scheme:
  - J transmitters transmit a data packet in P frames
  - Transmissions may be conjugated and time-reversed

$$P = \frac{J(J-1)}{2}$$

5. Cooperative STBC for Distributed Transmissions

- Received signal model

$$x_0(n) = \sum_{j=1}^{J}\sum_{l=0}^{L} h_j(l)s_j(n-l-d_j) + v_0(n)$$

$$\mathbf{x}_0(n) = \sum_{j=1}^{J} \mathrm{H}_j \mathbf{s}_j(n-d_j) + \mathbf{v}_0(n)$$

- Use a linear (maximal ratio) combiner for decoding

$$y_j(n) = \tilde{\mathbf{h}}_j^T \mathbf{x}_0(n) - \sum_{i=1}^{j-1} \mathbf{h}_i^T \mathbf{x}_{p_{i,j}}(n) + \sum_{k=j+1}^{J} \mathbf{h}_k^T \mathbf{x}_{p_{j,k}}(n)$$

- Decoding results: require a linear equalizer for symbol estimation

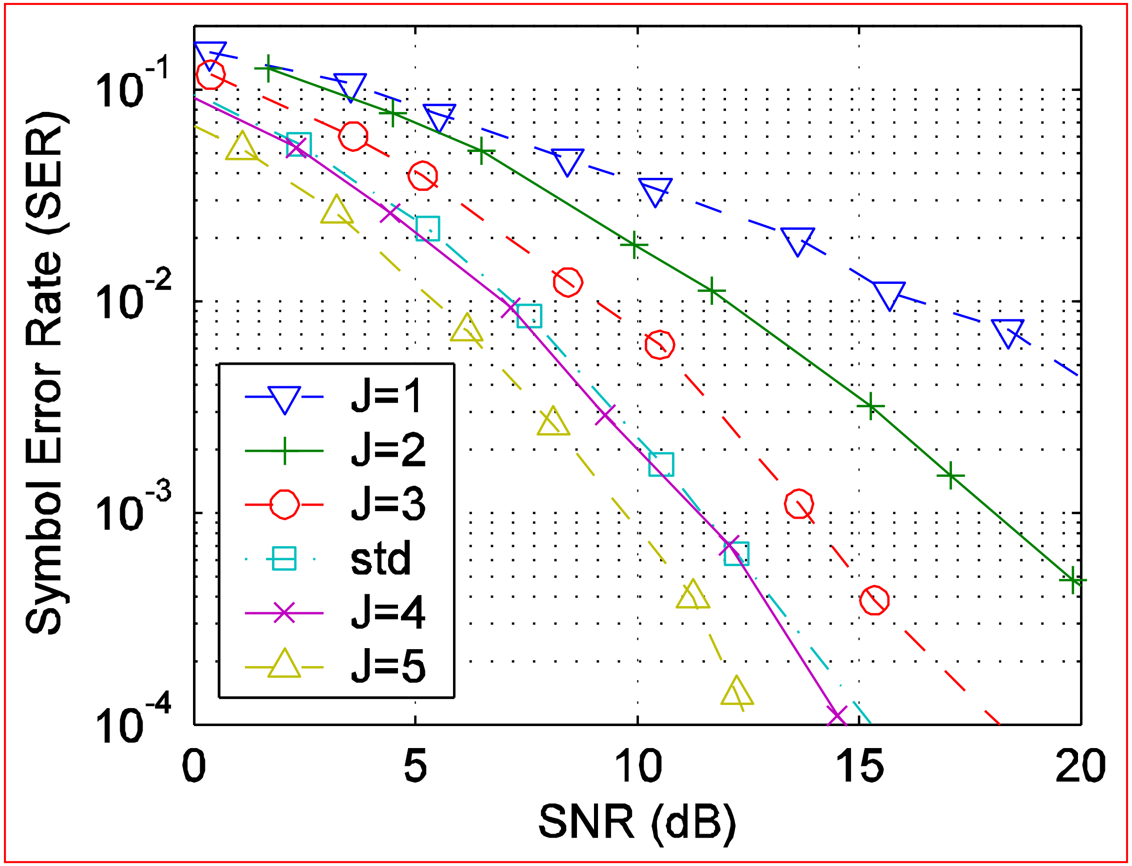
$$y_j(n) = \mathbf{g}^T \mathbf{s}_j(n-d_j) + w_j(n)$$

5. Cooperative STBC for Distributed Transmissions

- Properties
  - Tolerate asynchronous delays up to certain maximum bounds (reduce synchronization cost)
  - Linear complexity
  - Full diversity for any J cooperative nodes
  - Rate comparable to ordinary STBC for J=2 to 5 (1, ¾, 4/7, 5/11); but converges to 2/J for large J

5. Cooperative STBC for Distributed Transmissions

- Simulations: no loss of diversity while tolerating asynchronous transmissions

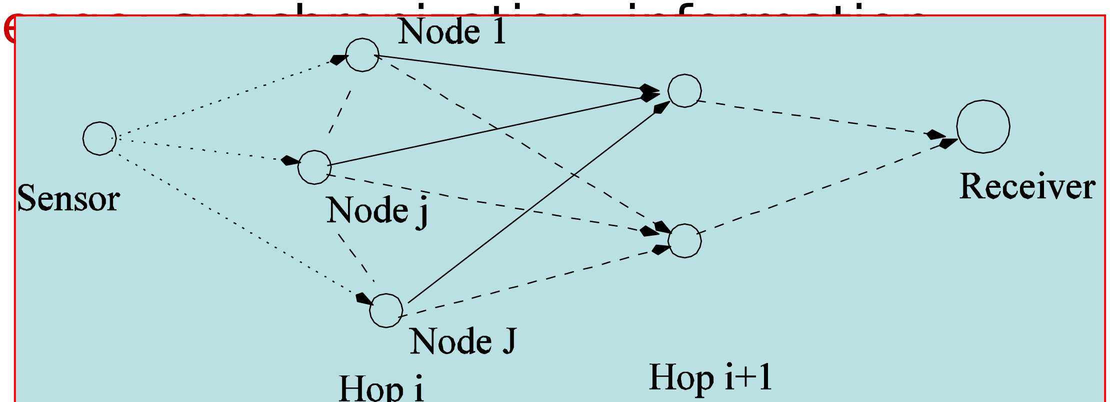


6. Secure WLAN with Collaborative Communications

- Collaborative communications provide wireless information assurance
  - wireless boundary control
  - location-based wireless intrusion detection
  - flexible response to intrusions
  - Anti-jam, low probability of interception
- Potential:
  - Make wireless networks as secure as wired networks
  - Provide a cost-effective way for enhancing existing and emerging wireless networks

6. Secure WLAN with Collaborative Communications

- Collaboration among multiple transmitters and/or multiple receivers
  - Cooperative transmission: directional transmission, beamforming
  - Cooperative receiving: directional receiving, beamforming,
  - Resolve the problem: mobiles have no antenna arrays
  - Major challenges: synchronization, information exchange



6. Secure WLAN with Collaborative Communications

- Beam Steering and Nulling

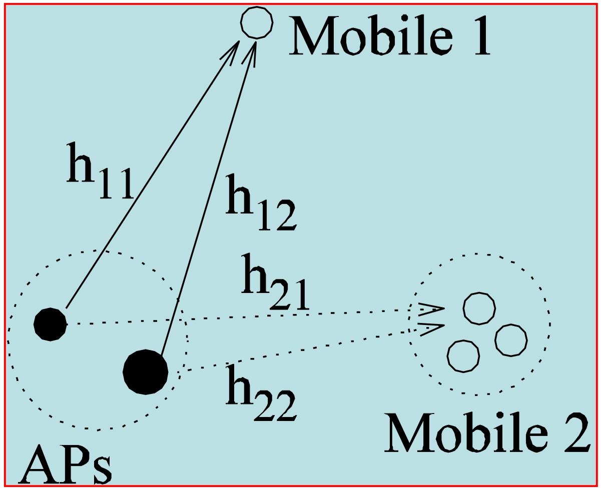
Apply beamform weights c_{1j} such tha

$$\sum_{j=1}^{J} c_{1j} h_{1j} = 1, \qquad \sum_{j=1}^{J} c_{1j} h_{kj} = 0, k \neq 1$$

Freedom in c_{1j} are used to randomize

the signal toward other directions

$$\sum_{j=1}^{J} c_{1j} g_j = random,$$



6. Secure WLAN with Collaborative Communications

- Wireless Boundary Control
  - Each group of transmitters provide detectible transmissions toward desired users only
  - Signals toward others are fast time-varying, randomized, and with reduced power
  - Low probability of intercept
  - Group of receivers cooperatively implement beamforming to mitigate interference/jam
- Challenges:
  - Channel feedback, data sharing among the transmitters, transmission synchronization, information exchange among receivers

6. Secure WLAN with Collaborative Communications

- Intrusion Detection and Response
  - Intrusion detection
    - Array of access points can locate every mobiles
    - Location information is displayed for visualization, just as camera-system-based building monitoring systems
    - Detect potential intruders in the very beginning
  - Intrusion response
    - Beam nulling toward the intruders
    - Location/channel based transmission: intrusion tolerance

6. Secure WLAN with Collaborative Communications

- Implementation Issues
  - Cost effective ways to enhance existing systems
    - Low cost: use multiple similar devices such as access points or relays
    - Compatible with existing or emerging systems: slight modification on physical-layer signal processing
  - Interesting and challenging works toward purely distributed processing
    - e.g., asynchronous cooperative communications, fault tolerant and optimal network designs with low cost nodes

Conclusions

- Defined collaborative communications
- Discussed benefits and major challenges
- Showed that cooperative transmission is useful for sensor networks
- Developed new cooperative STBC in asynchronous transmissions
- Discussed work toward wireless network security

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